

Tropical Cyclone Genesis and Sudden Changes of Track and Intensity in the Western Pacific

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LONG-TERM GOALS

The long-term goal of this project is to advance our understanding of the physical mechanisms involved in sudden changes in the tropical cyclone (TC) intensity/track and TC genesis and development processes in the western Pacific.

OBJECTIVES

To investigate both the large-scale environmental conditions and TC internal processes as well as their interactions that are responsible for TC genesis, rapid intensification (RI) and storm-scale structural changes.

Specific thrust areas include (1) mechanisms for some specific TC genesis processes, (2) the inner core structure changes and associated precursors before RI, (3) the processes controlling formation of concentric eyewalls and annular structure, and (4) the linkage between the large-scale environment sudden track change, and rapid intensity changes.

APPROACH

Our approach is to integrate observational analysis, numerical modeling, and diagnostic analysis to identify factors and elucidate the physical mechanisms that are responsible for TC genesis, RI, inner core structure and track changes. We analyze satellite observations and perform idealized and realistic numerical experiments with COAMPS, WRF and TCM4 models. We also apply diagnostic tools to study energetics, potential vorticity, angular momentum and heat and moisture budgets in order to elucidate mechanisms governing the internal cause structural and intensity changes.

People involved in this project are the PI, Co-PIs, PostDocs: Justin Ventham and Bo Yang, and graduate students: Xiaqiong Zhou, Bing Fu, Xuyang Ge and Christopher Chambers.

WORK COMPLETED

Here we highlight the works that have been published from January 2007 to September 2008 and recent submitted manuscripts. The current statuses of the works are indicated. For details of these works, please refer to the abstracts in the next section.

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(a) Tropical cyclone genesis (see abstract No. 1-7)

Our works on TC genesis through Rossby wave energy dispersion include three parts: observational analysis, three-dimension numerical model simulation under idealized conditions, and a real case study. These works have been completed. (Three papers were published and one was submitted)

A unique TC genesis cases over the western North Pacific (WNP) is documented. We found that the ancestor of unseasonal supper Typhoon Nanmadol (2004) is an upper tropospheric, counterclockwise rotating mixed Rossby-gravity (MRG) wave originated over the Eastern Pacific (near 120W). (Published in 2008)

Another unique TC genesis case, Typhoon Vamei (2001) that formed over the South China Sea and very close to the equator is studied with MM5 model. (Published in 2007)

The genesis processes of the most deadly tropical storm Nargis (2008) over Northern Indian Ocean is documented with multiple satellite observations. (Submitted)

(b) Tropical cyclone structure and intensity change (see abstract No. 8-14)

We identified and elucidated the climatic conditions that are critical to the frequency and location of the Rapid Intensification (RI) over WNP on annual, intraseasonal, and interannual time scales. (Published in 2008)

We also identified the large-scale synoptic environmental flow patterns around future intensifying tropical storms with the goal of finding the most favorable low-level flow fields for RI. (Published in 2007)

We extended the analysis of environmental dynamical control of tropical cyclone (TC) intensity performed previously for the western North Pacific to the North Atlantic. (Published in 2008)

Our work on the effect of internally generated inner-core asymmetries on tropical cyclone potential intensity has been completed and the work is published in 2007.

The formation and maintenance of the moat outside the primary eyewall of a TC is examined in a full physics TC model. (Published in 2008)

The MM5 was used to perform numerical experiments to understand the effects of terrain and land surface processes on the observed eyewall evolution. (In press)

(c) Formation of concentric eyewall and annular hurricane (see abstract No.15-17)

A new mechanism of the formation of concentric eyewall is proposed. The asymmetric forcing outside of the radius of maximum winds lead to, respectively the weakening and strengthening of the symmetric flow in the inner and outer regions due to the asymmetric up (down) shear tilting structure and such-induced symmetry-to-asymmetry (asymmetry-to-symmetry) energy transfer. This process leads double peaks in the symmetric tangential wind profile. (The paper is in press)

Two possible ways to the formation of an annular hurricane are suggested. The results from the idealized numerical model suggest that the concentric eyewall replacement would lead to the formation of an annular hurricane through sufficient PV mixing between the inner and outer eyewall. We also found that an AH forms as a result of several cycles of inward contraction of the inner spiral rainbands. (One paper is published and another paper is submitted)

(d) Large scale climate control of TC activity and others (See abstract No. 18-24)

Using the historical best track datasets from 1975 to 2004, we explained how the annual frequency, lifetime and intensity of tropical cyclones contribute to the changes in the annual accumulated power dissipation index (PDI). (Published in 2008)

We also found that changes in the proportion of the intense hurricanes over the past 30 years are attributed to changes in the TC formation locations and their prevailing tracks. We suggest that the response of the atmospheric circulation in TC basins to the global warming is more critical than increasing SST to understanding the impacts of global warming on tropical cyclone intensity. (Published in 2008)

The linear trend of the tropical cyclone (TC) potential intensity (PI) and its control parameters are investigated in a 15-model ensemble of Coupled Model Intercomparison Project/CMIP3 integrations during the first 70 years of a transient run forced by 1% per year CO₂ increase. (Submitted)

A new data assimilation method “3-dimensional variational data assimilation of mapped observation (3DVM)” is used in the TC bogus data assimilation (BDA). (Published in 2008)

Two phytoplankton blooms triggered by two typhoons with different intensities and translation speeds in the South China Sea (SCS) are compared. (Published in 2007)

A heavy rainfall event occurred in the southern central Japan and its adjacent seas is studied with WRF model. The results suggest that the northward moisture transport through the outer cyclonic circulation of Typhoon Songda (2004) more than 1,200 km away contributes to the heavy rainfall event. (Submitted)

The global Nonhydrostatic ICosahedral Atmospheric Model (NICAM) with cloud--resolved resolutions successfully reproduced the lifecycles of two real tropical cyclones that formed in Indian Ocean in the austral summer 2006. The promising results presented suggest the predictability of tropical cyclones by high-resolution global cloud-system-resolving models. (Submitted)

RESULTS (ABSTRACTS)

1. Analysis of Tropical Cyclogenesis in the Western North Pacific for 2000 and 2001 (*Fu, B., T. Li, M. Peng, and F. Weng 2007*)

High-resolution satellite data and NCEP-NCAR reanalysis data are used to analyze 34 tropical cyclone (TC) genesis events in the western North Pacific (WNP) during its 2000 and 2001 typhoon seasons. Three types of synoptic-scale disturbances are identified in the pre-genesis stages that can be linked to TC genesis. They are tropical cyclone energy dispersion (TCED), synoptic wave trains (SWT) that are not associated with pre-existing TCs and easterly waves (EW). Among the total 34 TC genesis cases,

six are associated with TCED, eleven cases are associated with SWT and seven cases are associated with EW.

Our analyses indicate that the occurrence of TCED depends on the intensity of the previous TC and the background flow, with stronger cyclones and weaker background easterlies more likely to induce a Rossby wave train. Still, not all Rossby wave trains would lead to the formation of a new TC. Among the eleven SWT cases, four cases are triggered by equatorial mixed Rossby-gravity waves. Cyclogenesis events associated with EW are identified by westward propagation of perturbation kinetic energy and precipitation fields. For all three types of pre-storm disturbances, we suggest that scale contraction of the disturbances and convergence forcing from the large-scale environmental flow are possible mechanism leading to the genesis. Tropical intraseasonal oscillations have a significant modulation on TC formation, especially in 2000.

Further examination of the remaining 10 genesis cases with no significant prior synoptic-scale surface signals suggests three additional possible genesis scenarios: 1) disturbance with upper-tropospheric forcing, 2) interaction of a preexisting TC with southwesterly monsoon flows, and 3) preexisting convective activities with no significant initial low-level vorticity.

2. Tropical Cyclone Energy Dispersion in a Three-Dimensional Primitive Equation Model: Upper Tropospheric Influence (*Ge X.-Y., T. Li., Y. Wang, and M. Peng 2008*)

The three-dimensional (3D) Rossby wave energy dispersion of a tropical cyclone (TC) is studied using a baroclinic primitive equation model. The model is initialized with a symmetric vortex on a beta-plane in an environment at rest. The vortex intensifies while becoming asymmetric and moving northwestward due to the beta effect, and a synoptic-scale wave train forms in its wake a few of days later. The energy-dispersion induced Rossby wave train has a noticeable baroclinic structure with alternating cyclonic-anticyclonic-cyclonic (anticyclonic-cyclonic-anticyclonic) circulations in the lower (upper) troposphere. A key feature associated with the 3D wave train development is a downward propagation of the relative vorticity and kinetic energy. Due to the vertical differential inertial stability, the upper level wave train develops faster than the lower level counterpart. The upper anticyclonic circulation rapidly induces an intense asymmetric outflow jet at the southeast quadrant, and then further influences the lower-level Rossby wave train. On one hand, the outflow jet exerts an indirect effect on the lower-level wave train strength through changing TC intensity and structure. On the other hand, it triggers downward energy propagation that further enhances the lower level Rossby wave train. A sudden removal of the diabatic heating may initially accelerate the energy dispersion through the increase of the radius of maximum wind and the reduction of the lower level inflow. The latter may modulate the group velocity of the Rossby wave train through the Doppler shift effect. The 3D numerical results illustrate more complicated Rossby wave energy dispersion characteristics than 2D barotropic dynamics.

3. Tropical Cyclone Energy Dispersion under Vertical Shears (*Ge, X., T. Li, and X. Zhou 2007*)

Tropical cyclone Rossby wave energy dispersion under easterly and westerly vertical shears is investigated in a baroclinic model. In a resting environment, the model simulates a Rossby wave train that has a realistic baroclinic structure with alternating cyclonic-anticyclonic-cyclonic (anticyclonic-cyclonic-anticyclonic) circulations in the lower (upper) troposphere. A significant asymmetry appears in the wave train development under easterly and westerly vertical shears, that is, an easterly (westerly) shear confines the maximum amplitude of the wave train primarily to the lower (upper) level. It is

proposed that the vertical wind shear may impact the Rossby wave train development through both the barotropic-baroclinic mode coupling and the modulation of the group velocity by the mean flow through a “Doppler shift effect”. Additional experiments with uniform westerly and easterly mean flows are conducted to verify the above mechanisms. The enhancement of the Rossby wave train in the lower level by the easterly shear may have an important implication for understanding the tropical cyclogenesis and the origin of the synoptic wave trains in the western North Pacific.

4. Simulation of Typhoon Prapiroon (2000) genesis associated with Rossby wave energy dispersion (*Ge, X., T. Li, and M. Peng 2008*)

The genesis of Typhoon Prapiroon (2000) is simulated to understand the possible roles of energy dispersion from a previous storm in triggering Prapiroon. Two experiments are conducted. In CTL, we retain both the pre-existing TC and its wave train in the initial fields. In EXP, we remove the typhoon core of the pre-existing storm while keeping its wave train, serving as the precursor of Prapiroon. The numerical simulations demonstrate the important role of the pre-existing TC plays in the subsequent TC genesis through both direct and indirect contributions. The direct contribution comes from a continued deposit of energy by the Rossby wave energy dispersion of the pre-existing storm. The indirect contribution is through the generation of the secondary circulation induced by the upper-level outflow jet of the previous storm. A divergence tendency to the left side of the outflow jet-exit region is diagnosed that enhances the large-scale convection and lower-level convergence, thus provides a favorable condition for the subsequent TC development.

5. Transition from an eastern Pacific upper-level mixed Rossby-gravity wave to a western Pacific tropical cyclone (*Zhou X. and B. Wang 2007*)

The ancestor of unseasonal Typhoon Nanmadol (2004) over the western North Pacific is traced back to the Eastern Pacific (near 120W) as an upper tropospheric, counterclockwise rotating mixed Rossby-gravity (MRG) wave. The temporal and spatial evolution from an equatorial trapped MRG-wave-type disturbance to an off-equatorial tropical depression is documented by utilizing NOGAPS (Navy’s Operational Global Atmospheric Prediction System) analysis data. It is found that the MRG wave moved away from the equator after a dramatic reduction in its zonal dimension and downward development and amplification in the lower troposphere. These dramatic changes in MRG wave properties are attributed to the modulation of the easterly vertical shear, low-level westerly-easterly confluence in the large-scale background flows, and convective coupling, as well as underlying high sea surface temperature (SST). The boundary layer convergence associated with asymmetric pressure field of the MRG wave is likely responsible for the transition from an equatorial MRG to an off-equatorial tropical disturbance. This case study addresses the possibility that upper tropospheric MRG waves over the far eastern Pacific may provide “seeds” for tropical cyclogenesis over the western North Pacific.

6. Simulation of Formation of a Near-Equatorial Typhoon Vamei (2001) (*Chambers, C., and T. Li 2007*)

A community mesoscale model is used to simulate and understand processes that led to the formation and intensification of the near-equatorial Typhoon Vamei that formed in the South China Sea in December, 2001. The simulated typhoon resembles the observed in that it had a short lifetime and a small size, formed near the equator (south of 2°N), and reached category-one intensity. The formation involved the interactions between the scales of the background cyclonic circulation (the Borneo Vortex

of order ~ 100 km) and of mesoscale convective vortices (MCVs, in the order ~ 10 km). Before tropical cyclone formation MCVs formed along a convergent, horizontal shear vorticity line on the eastern edge of an exceptionally strong monsoonal northerly wind surge.

The typhoon genesis is marked by three rapid intensification periods, which are associated with the rapid growth of potential vorticity (PV). A vorticity budget analysis reveals that the increases in low-level vorticity during the rapid intensification periods are attributed to enhanced horizontal vorticity fluxes into the storm core. The increase of the horizontal vorticity flux is associated with the merging of areas of high PV associated with MCVs into the storm core as they are advected by background cyclonic flows. The increases in PV at upper levels are associated with the evaporation of upper level stratiform precipitation and increases of vertical potential temperature gradient below the maximum stratiform cloud layer. It appears that two key sources of PV at upper and lower levels are crucial for the build up of high PV and a deepening of a cyclonic layer throughout the troposphere.

7. Genesis of tropical cyclone Nargis revealed by multiple satellite observations. (*Kazuyoshi K., B. Wang and H. Fudeyasu 2008*)

Tropical cyclone (TC) Nargis recently battered Myanmar on May 2 2008 is one of the most deadly tropical storms. Its initiation and formation processes are investigated by using multiple satellite observations. Nargis was initiated by northeastward shift of Madden-Julian oscillation convection in the eastern Indian Ocean. The collocation between well-built surface winds and active convection makes it possible to create a central warm-core structure, forming the tropical depression (TD) on April 26. The TC formation is characterized by two distinctive stages: a radial contraction followed by a rapid intensification. The middle tropospheric warming near the TD center lowers surface pressure, resulting in contraction of the band of maximum winds and convection. When the contraction reaches a certain threshold, rapid intensification occurred as a result of deep convection development followed by axisymmetrization process. This new scenario is instrumental for understanding how a major TC develops in the northern Indian Ocean.

8. Climate Variation and Prediction of Rapid Intensification in Tropical Cyclones in the Western North Pacific (*B. Wang and X. Zhou 2008*)

One of the greatest challenges in tropical weather forecasting is the rapid intensification (RI) of the tropical cyclone (TC), during which its one-minute maximum sustained wind speed increases at least 30 knots per 24 hours. Here we identify and elucidate the climatic conditions that are critical to the frequency and location of the RI on annual, intraseasonal, and interannual time scales. Whereas RI and formation share common environmental preferences, we found that the percentage of TCs with RI varies annually and from year to year. In August, only 30% of TC actually experiences RI, in contrast to the annual maximum of 47% in November. The proportion of RI in July-September is higher during El Nino years (53%) than the corresponding one in the La Nina years (37%).

Three climate factors may contribute to the increase in the proportion of RI: the southward shift in the monthly or seasonal mean location of the TC formation, the increase in the low-level westerly meridional shear vorticity, and the decrease in northerly vertical shear. When the mean latitude of TC formation increases, the mixed-layer heat content decreases while TC's inertial stability increases; both are more detrimental to the RI than to TC formation because the RI requires large amount of latent heat energy being extracted efficiently from the ocean mixed layer and requires accelerated low-level radial inflow that carries latent heat reaching the inner core region. We further demonstrate that the RI

frequency in the Philippine Sea and South China Sea can be predicted 10 to 30 days in advance based on the convective anomalies in the equatorial western Pacific (5°S-5°N, 130°-150°E) on intraseasonal time scale. The NINO3.4 SSTA in June is a potential predictor for the peak TC season (July-September) RI activity in the southeast quadrant of the western North Pacific (0-20°N, 140-180°E).

The RI is an essential characteristic of category 4 and 5 hurricanes and super typhoons because all category 4 and 5 hurricanes in the Atlantic basin and 90% of the super typhoons in the western North Pacific experience at least one RI process in their life cycles. Over the past 40 years, the annual total of RI in the western North Pacific shows pronounced interdecadal variation but no significant trend. This result suggests that the number of super typhoons has no upward trend in the past 40 years. Our results also suggest that when the mean latitude, where the tropical storms form, shifts southward (either seasonally or from year to year) the proportion of super typhoon or major hurricane will likely increase. This shift is determined by large scale circulation change rather than local SST effects. This idea differs from the current notion that increasing SST can lead to more frequent occurrence of Category 4 or 5 hurricanes through local thermodynamics.

9. Large scale flow patterns and their influence on the intensification rates of western north Pacific tropical storms. (Ventham, J. D., and B. Wang, 2007)

Large scale environmental flow patterns around future intensifying tropical storms are identified with the goal of finding the most favorable low-level flow fields for RI. The analysis is, based on the hypothesis that aspects of the horizontal flow may affect TC intensification at the early stage. A new initial intensity-based definition of RI is proposed and is used to define very rapid, rapid and slow 24 hr intensification periods from weak tropical storm stage (35 kts). By using composite analysis and scalar EOF analysis of the zonal wind around these subsets, a form of the lower level (850 mb) monsoon confluence pattern is found to occur dominantly for the very rapid cases. At 200 mb the importance of the location of the incipient tropical storm directly under a region of flow splitting into the mid-latitude westerlies to the north and the sub-equatorial trough to the south is identified as a common criterion for the onset of RI (as well as an eastward extension of outflow south of the TUTT). The total 200 mb slow composite exists in an upper level environment with north-easterlies over the lower level tropical storm, and without outflow to the north

10. An observational study of environmental dynamical control of tropical cyclones intensity in the North Atlantic (Zeng, Z., L.-S. Chen, and Y. Wang, 2008)

An attempt has been made to extend the analysis of environmental dynamical control of tropical cyclone (TC) intensity recently performed for the western North Pacific to the North Atlantic. The results show that both the vertical shear and translational speed have negative effects on TC intensity, consistent with previous findings for other basins. It is shown that few TCs intensified when they moved faster than 15 m s^{-1} . The threshold vertical shear of 20 m s^{-1} , which is defined as the difference of total winds between 200 hPa and 850 hPa averaged within 5° latitudes around the TC center, is found above which few TCs intensified and below which most TCs could reach their lifetime peak intensity. The average intensity of total TCs in the Atlantic is a bit smaller than that in the western North Pacific. The SST-determined empirical TC maximum potential intensity (EMPI) for 1981-2003 in this study is slightly higher than that found for 1962-1992 by DeMaria and Kaplan in the Atlantic, however.

To be consistent with the theoretical TC MPI, a new EMPI has been constructed, which includes the effect of thermodynamic efficiency. This new EMPI improves the estimation of real TC maximum intensity marginally due to the fact that the thermodynamic efficiency is largely determined by SST. To include the environmental dynamical control of TC intensity, a dynamical efficiency has been introduced, which is inversely proportional to the combined amplitude of vertical shear and translational speed. With this dynamical efficiency, an empirical maximum intensity (EMI) for Atlantic TCs has been constructed. This EMI includes not only the positive contribution by SST but also the effects of both thermodynamic and dynamical efficiencies. It provides more accurate estimations of TC maximum intensity. Furthermore, the formulation of the new EMI explains the observed behavior of TC maximum intensity by thermodynamic and dynamical controls in a transparent and easy to interpret manner.

11. The Effect of Internally Generated Inner-Core Asymmetries on Tropical Cyclone Potential Intensity (*B. Yang, Y. Wang, and B. Wang 2007*)

In a quiescent environment on an f plane, the internal dynamic processes of a tropical cyclone (TC) can generate axially asymmetric circulations (asymmetries) in its inner-core region. The present study investigates how these inner-core asymmetries affect TC Intensity. For this purpose, a three-dimensional (3D) TC model and its axisymmetric (2D) version were used. Both have identical model vertical structure and use the same set of parameters and the same initial conditions. The differences between the two model runs are considered to be due to mainly the effects of the TC asymmetries. The results show that the presence of asymmetries in the 3D run reduces the TC final intensity by about 15% compared with the 2D run, suggesting that the TC asymmetry is a limiting factor to the potential intensity (PI).

In the 2D run without asymmetries, the convective heating in the eyewall generates an annular tower of high potential vorticity (PV) with relatively low PV in the eye. The eyewall tilts outward with height significantly. Underneath the tilted eyewall the downdrafts induced by evaporation of rain and melting of snow and graupel make the subcloud-layer inflow dry and cool, which lowers the boundary layer equivalent potential temperature (θ_e), thus increasing the entropy difference between the air and sea in the vicinity of the radius of maximum wind (RMW). The increased air–sea entropy deficit leads to more energy input into TC from the underlying ocean and thus a greater final intensity. On the other hand, in the 3D run, the model-resolved asymmetric eddies, which are characterized by the vortex Rossby waves in the mid-lower troposphere, play important roles in modifying the symmetric structure of the TC. Potential vorticity and θ_e budgets indicate that significant inward PV mixing from the eyewall into the eye results in a less-tilted eyewall, which in turn limits the drying and cooling effects of downdrafts in the subcloud layer and reduces the air–sea entropy deficit under the eyewall, thereby reducing the TC intensity. The angular momentum budget analysis shows that the asymmetric eddies tend to reduce the strength of the primary circulation in the vicinity of the RMW. This eddy contribution to the azimuthal mean angular momentum budget is larger than the parameterized horizontal diffusion contribution in the 3D run, suggesting an overall diffusive effect of the asymmetric eddies on the symmetric circulation.

12. How do outer spiral rainbands affect tropical cyclone structure and intensity? (*Wang, Y., 2008*)

A long-standing issue on how outer spiral rainbands affect the structure and intensity of tropical cyclones is studied through a series of numerical experiments using the cloud-resolving tropical

cyclone model TCM4. Since diabatic heating due to phase changes is the main driving force of outer spiral rainbands, their effect on the tropical cyclone structure and intensity is evaluated by artificially modifying the heating/cooling rate from cloud microphysical processes in the model. The effect of diabatic heating due to phase changes in outer spiral rainbands on the storm structure and intensity is understood based mainly on the hydrostatic adjustment. Namely, heating (cooling) in an atmospheric column would result in a decreasing (increasing) tendency in surface pressure underneath. This, in turn, would affect the horizontal pressure gradient and thus winds across the radius of maximum wind in the lower troposphere. The results show that cooling in outer spiral rainbands is important to both intensity of the tropical cyclone and the maintenance of a relatively compact inner core structure, while heating in outer spiral rainbands is negative to the storm intensity but favors the increase in storm size. Overall, the presence of active outer spiral rainbands limits the intensity of tropical cyclones. Since heating and cooling outside the inner core in outer spiral rainbands depends strongly on the relative humidity in the near core environment, implications of the results to the formation of the annular hurricane structure, the concentric eyewall cycle, and the size change of tropical cyclones are discussed.

13. Rapid filamentation zone in a numerically simulated tropical cyclone (Wang, Y., 2008)

In a recent study, Rozoff et al. (2006) proposed a possible mechanism to explain the formation and maintenance of the moat outside the primary eyewall of a TC observed on radar images. By this mechanism, the moat is considered to be a region of the strain-dominated flow outside the RMW in which essentially all fields are filamented and deep convection is hypothesized to be highly distorted and even suppressed. This strain-dominated region is defined as the rapid filamentation zone wherein the filamentation time is shorter than the overturning time of deep convection. This work attempted to test the hypothesis in a full physics TC model under idealized conditions and to extend the concept to the study of the inner core dynamics of TCs. The results show that instead of suppressing deep convection, the strain flow in the rapid filamentation zone outside the RMW provides a favorable environment for the organized inner spiral rainbands. Although the moat in the simulated TC is located in the rapid filamentation zone, it is mainly controlled by the subsidence associated with the overturning flow from eyewall convection and downdrafts from the anvil stratiform precipitation outside the eyewall. It is thus suggested that rapid filamentation be likely to play a secondary role in the formation of the moat in TCs. Because of strong straining deformation, asymmetries with azimuthal wavenumber > 4 are found to be damped effectively in the rapid filamentation zone. The filamentation time thus provides a quantitative measure of the stabilization and axisymmetrization of high wavenumber asymmetries in the inner core by shearing deformation and filamentation.

14. A numerical investigation of the eyewall evolution of a landfalling typhoon (Wu, C.-C., H.-J. Cheng, Y. Wang, and K.-H. Chou, 2008)

An interesting eyewall evolution occurred in Typhoon Zeb (1998) when it devastated Luzon. The eyewall of Zeb shrank before landfall, broke down and weakened after landfall, and a much larger new eyewall formed and strengthened as it left Luzon and reentered the ocean. The MM5 model with four nested domains was used to perform numerical experiments to understand the effects of terrain and land surface processes on the observed eyewall evolution. Results show that the presence of Luzon plays a critical role in leading to the observed eyewall evolution. Quite different from the conventional concentric eyewall replacement, the eyewall replacement occurred in Typhoon Zeb was triggered by the mesoscale landmass and terrain that has a horizontal scale similar to the core of the typhoon. In Typhoon Zeb, the original eyewall shrank and breakdown due to enhanced surface friction after

landfall. The outer eyewall is triggered near the western coastal region of Luzon and formed as a result of axisymmetrization well after the dissipation of the inner eyewall convection. Several sensitivity experiments were also conducted to elucidate the importance of both moist and planetary boundary layer processes in the evolution of the typhoon eyewall. It is found that although the diabatic heating is the key to the maintenance of the annular potential vorticity (PV) structure, surface friction plays an important role in keeping the PV annulus narrow by enhancing the vorticity stretching in the lower troposphere.

15. From Concentric Eyewall to Annular Hurricane: A Numerical Study with the Cloud-Resolved WRF Model (Zhou X. and B. Wang 2008)

Observations have revealed that Hurricane Daniel (2006) over the Eastern Pacific formed following an eyewall replacement (concentric eyewall) process. The transformation from a non-annular hurricane to an annular hurricane through a concentric eyewall and eyewall replacement process is simulated for the first time with the cloud-resolved Weather Research and Forecasting (WRF) model in a resting environment on a constant f -plane. The model simulated intense hurricane experiences a three-stage evolution: the formation of the secondary eyewall, the eyewall replacement, and the formation of an annular hurricane with large eye, thick eyewall, and suppressed outer rainbands. The simulated eyewall succession and accompanying intensity change are generally consistent with observations. The storm evolves into an annular hurricane within 24 hours after the eyewall replacement, suggesting a new, efficient route to formation of annular hurricane. The results also suggest that the formation of a concentric eyewall and an annular hurricane can be entirely due to its internal dynamics/thermodynamics. It is demonstrated that the WRF model has potential to predict the remarkable eyewall evolution processes and related intensity change. Physical processes involved are discussed.

16. Formation of tropical cyclone concentric eyewalls by wave-mean flow interactions (Peng, J., T. Li, and M. Peng 2008)

The role of two-way interactions between a symmetric core vortex and an asymmetric disturbance in generating TC concentric eyewalls is examined in a nonlinear barotropic model. The results show that when an asymmetric perturbation is placed outside of the radius of maximum wind, an asymmetric disturbance develops in the inner region, resulting in a weakening of the symmetric flow in situ, while the symmetric tangential wind gains energy from the asymmetric perturbations in the outer region. This process leads double peaks in the symmetric tangential wind profile. Further diagnosis reveals that the distinctive evolution features in the inner and outer regions are determined by the asymmetric up (down) shear tilting structure and so-induced symmetry-to-asymmetry (asymmetry-to-symmetry) energy transfer. There exists an optimal radius location for the initial perturbation to generate most efficiently a double-peak structure in the symmetric tangential wind profile.

17. Structure and formation of an annular hurricane simulated in TCM4 (Wang, Y., 2008)

This work analyzed the structure and formation of an annular hurricane simulated in TCM4. The simulated annular hurricane has all characteristics of those recently documented by Knaff et al. (2003) from satellite observations: quasi-axisymmetric structure, large eye and wide eyewall, high intensity, and suppressed major spiral rainbands. A striking feature of the simulated annular hurricane is its large outward tilt of the wide eyewall, which is critical to the quasi-steady high intensity and is responsible for the maintenance of the large size of the eye and eyewall of the storm. The formation of the

simulated annular hurricane is closely related to the interaction between the inner spiral rainbands and the eyewall convection. As the inner rainbands spiral cyclonically inward, they may experience axisymmetrization due to strong shear deformation and filamentation outside the eyewall and evolve into a quasi-symmetric convective ring, which intensifies as it contracts while the eyewall breaks down and weakens. Eventually, the convective ring replaces the original eyewall. The new eyewall formed in such a way is wider and tilts more outward with height than the original eyewall. Several such eyewall cycles produce a typical annular hurricane. The response of low-level tangential winds to the tilted convective heating in the eyewall is an increase/decrease outside/inside the RMW, prohibiting a further contraction of the new eyewall. Strong convective massflux in the eyewall updraft corresponds to strong convective overturning subsidence, greatly suppressing any major rainbands outside the eyewall. Although the eyewall cycle documented in this work contributes to the formation of annular hurricanes, it could be one of the processes causing the increase in eye size of real TCs.

18. Implications of Tropical Cyclone Power Dissipation Index (*Liguang Wu, Bin Wang, and Scott A. Braun, 2008*)

Upward trends in the power dissipation index (PDI) in the North Atlantic (NA) and western North Pacific (WNP) basins and increases in the number and proportion of intense hurricanes (categories 4 and 5) in all tropical cyclone basins have been reported in recent studies. These changes have been arguably viewed as an evidence of the responses of tropical cyclone intensity to the increasing tropical sea surface temperature (SST) over the past 30 years. Using the historical best track datasets from 1975 to 2004, how the annual frequency, lifetime and intensity of tropical cyclones contribute to the changes in the annual accumulated PDI is examined. As the SST warmed in the NA, WNP and eastern North Pacific (ENP) basins over the past 30 years, the annual accumulated PDI trended upward significantly only in the NA basin, where the decreased vertical wind shear and warming ocean surface may have allowed more storms to form and to form earlier or dissipate later, increasing the lifetime and annual frequency of tropical cyclones. The moderate increase in the annual accumulated PDI in the WNP basin was primarily due to the significant increase in the average intensity. There are no significant trends in the accumulated PDI, average intensity, average lifetime, and annual frequency in the ENP basin.

19. What have changed the proportion of intense hurricanes in the last 30 years? (*Liguang Wu and Bin Wang, 2008*)

The recently reported increase in the proportion of intense hurricanes is considerably larger than those projected by the maximum potential intensity (MPI) theory and the results of numerical simulation. To reconcile this discrepancy, we examined the best track datasets for the North Atlantic (NA), western North Pacific (WNP), and eastern North Pacific (ENP) basins. We found that the changes in the tropical cyclone formation locations and prevailing tracks may have contributed to the changes in the proportion of the intense hurricanes over the past 30 years. We suggest that the changes in the formation locations and prevailing tracks have a profound impact on the basin-wide tropical cyclone intensity. Thus, how the atmospheric circulation in the tropical cyclone basins responds to the global warming may be a critical factor to understanding the impacts of global warming on tropical cyclone intensity.

20 Response of Tropical Cyclone Potential Intensity to the Global Warming Scenario in the IPCC AR4 CGCMs (*J.-H. Yu, Y. Wang, K. Hamilton, 2008*)

This reports on an analysis of the tropical cyclone (TC) potential intensity (PI) and its control parameters in transient global warming simulations. Specifically the TC PI is calculated for a 15-model ensemble of Coupled Model Intercomparison Project/CMIP3 integrations during the first 70 years of a transient run forced by 1% per year CO₂ increase. The linear trend over the period is used to project the 70-year change in relevant model parameters. The annual mean sea surface temperature (SST) averaged over all oceans between 30°S~30°N is found to increase by 1.54°C. The warming is small in the North Atlantic while has a spatial pattern in the equatorial Pacific similar to the distribution in SST anomaly in the mature phase of an El Niño event. The outflow layer temperature also increases, thus the thermodynamic efficiency changes little among all TC basins. The relative humidity (RH) changes little at 1000 hPa while it decreases significantly at 700 hPa over the North Atlantic and eastern Pacific. The thermodynamic potential intensity (THPI) increases on average 1.0%~3.1% over various TC basins in the transient response to the doubled CO₂ concentration. Dynamical control modifies the rate of change in the TC THPI significantly through the dynamical efficiency which takes into account the effect of vertical shear. In particular, the THPI shows a modest increase but modified PI including the dynamical control shows a weak decrease or little changes over the North Atlantic in the transient response to the doubled CO₂ concentration. The largest increase in both the THPI and dynamically modified PI due to the CO₂ is projected to occur in Indian Ocean region.

21. Initialization and simulation of a landfalling typhoon using a variational bogus mapped data assimilation (BMDA) (*Zhao, Y., B. Wang, and Y. Wang, 2007*)

Recently, a new data assimilation method called “3-dimensional variational data assimilation of mapped observation (3DVM)” has been developed by the authors. We have shown that the new method is very efficient and inexpensive compared with its counterpart 4-dimensional variational data assimilation (4Dvar). The new method has been implemented into the Penn State/NCAR mesoscale model MM5V1 (MM5_3DVM). In this study, we apply the new method to the bogus data assimilation (BDA) available in the original MM5 with the 4Dvar. By the new approach, a specified sea level pressure (SLP) field (bogus data) is incorporated into MM5 through the 3DVM (for convenient, we call it variational bogus mapped data assimilation–BMDA) instead of the original 4Dvar data assimilation. To demonstrate the effectiveness of the new 3DVM method, initialization and simulation of a landfalling typhoon—Typhoon Dan (1999) over the western North Pacific with the new method are compared with that with its counterpart 4Dvar in MM5. Results show that the initial structure and the simulated intensity and track are improved more significantly using 3DVM than 4Dvar. Sensitivity experiments also show that the simulated typhoon track and intensity are more sensitive to the size of the assimilation window in the 4Dvar than that in the 3DVM. Meanwhile, 3DVM takes much less computing cost than its counterpart 4Dvar for a given time window.

22. Comparison of phytoplankton blooms triggered by two typhoons with different intensities and translation speeds in South China Sea (*Zhao, H., D.-L. Tang, and Y. Wang, 2008*)

Two phytoplankton blooms triggered by two typhoons with different intensities and translation speeds in the South China Sea (SCS) are compared using remote sensing data of chlorophyll-a (Chl-*a*), sea surface temperature (SST), vector wind fields, and the best-track typhoon data. Typhoon Ling_Ling (2001) was a category 4 storm with maximum sustained surface wind speed of 59m s⁻¹ and fast-moving at a mean translation speed of 4.42 m s⁻¹. Typhoon Kai_Tak (2005) was a category 2 storm

with its maximum sustained surface wind speed of 46 m s^{-1} and slow-moving with a mean translation speed of 2.9 m s^{-1} . It is shown that the slow-moving typhoon induced phytoplankton blooms of higher Chl-*a* concentration, whereas the strong typhoon induced blooms over a larger area. About 7 typhoons on average per year affect the SCS, among which 41% are strong and 59% are weak, and about 64% are fast-moving and 36% are slow-moving. It is estimated that these typhoons might contribute 16% to the annual new primary production in the oligotrophic SCS.

23. A Numerical Study of the Effect of Typhoon Songda (2004) on Remote Heavy Rainfall in Japan (*Y.-Q. Wang, Y. Wang, H. Fudeyasu, 2008*)

When Typhoon Songda (2004) was located southeast of Okinawa over the western North Pacific during 2 to 4 September 2004, a heavy rainfall event occurred in the southern central Japan and its adjacent seas, more than 1,200 km from the typhoon center. The Advanced Weather Research and Forecast (WRF, also ARW) model was used to investigate the possible effect of Typhoon Songda on the remote precipitation in Japan. The National Centers for Environmental Prediction (NCEP) global final (FNL) analysis was used to provide both the initial and lateral boundary conditions for the WRF model. The model was initialized at 18 UTC 2 September and integrated until 18 UTC 6 September 2004 during which Songda was a super typhoon. Two primary numerical experiments were performed. In the control experiment, a bogus vortex was inserted into the FNL analysis to enhance the initial storm intensity such that the model typhoon had an intensity similar to the observed at the initial time. In the no-typhoon experiment, the vortex associated with Typhoon Songda in the FNL analysis was removed by a smoothing algorithm such that the typhoon signal did not appear at the initial time.

As verified against various observations, the control experiment captured reasonably well the evolution of the storm and the spatial distribution and evolution of precipitation, while the remote precipitation in Japan was largely suppressed in the no-typhoon experiment, indicating a significant far-reaching effect of Typhoon Songda. It is found that Songda enhanced the remote precipitation in Japan through two major processes. Its outer cyclonic circulation, on one hand, enhanced the northward moisture transport into the precipitation region, and on the other hand, it contributed to a strong moist frontogenesis of the original precipitation system through enhancing the deformation fields in the middle-lower troposphere. Both effects are crucial to the observed heavy rainfall in Japan. It is also shown that the orographic forcing of the central mountains in Japan played a secondary role compared with Typhoon Songda in the extreme precipitation event studied.

24. The Global Cloud-System-Resolving Model NICAM Successfully Simulated the Lifecycles of Two Real Tropical Cyclones (*Fudeyasu, H., Y. Wang, M. Satoh, T. Nasuno, H. Miura, W. Yanase, 2008*)

The increasing capability of high-end computers allows numerical simulations with horizontal resolutions high enough to resolve cloud systems in a global model. In this paper, initial results from the global Nonhydrostatic ICosahedral Atmospheric Model (NICAM) are highlighted to demonstrate the beginning of a potentially new era for weather and climate predictions with global cloud-system-resolving models. The NICAM simulation with a horizontal resolution of about 7 km successfully reproduced the lifecycles of two real tropical cyclones that formed in Indian Ocean in the austral summer 2006. Initialized with the atmospheric conditions 1-2 weeks before the cyclones genesis, the model captured reasonably not only the timing of the observed cyclone geneses but also their motions and mesoscale structures. The model provides a high temporal/spatial resolution dataset for detailed

studies of mesoscale aspects of tropical cyclone genesis. The promising results presented suggest the predictability of tropical cyclones by high-resolution global cloud-system-resolving models.

IMPACT/APPLICATIONS

Our observational and numerical modeling results are uncovering the relevant physical processes related to the tropical cyclogenesis, tropical cyclone structures especially some special eyewall features and associated intensity changes. We expect this to provide invaluable guidance for tropical cyclone genesis and intensity forecasting.

HONORS/AWARDS/PRIZES

Dr. Bin Wang in the University of Hawaii is elected as 2008 AMS fellow.

REREFEEED PUBLICATIONS (January 2007 - September 2008)

2007

- Chambers, C., and T. Li, 2007: Simulation of formation of a near-equatorial Typhoon Vamei (2001), *Meteor. Atmos. Phys.*, **98**, 67-80.
- Fu, B., T. Li, M. Peng, and F. Weng, 2007: Analysis of tropical cyclone genesis in the western North Pacific for 2000 and 2001. *Weather Forecasting*, **22**, 763-780.
- Ge, X., T. Li, Y. Wang, and M. Peng, 2008: Tropical Cyclone Energy Dispersion in a Three-Dimensional Primitive Equation Model: Upper Tropospheric Influence. *J. Atmos.Sci.*, **65**, 2271-2289.
- Ge X., T. Li and X. Zhou, 2007: Tropical cyclone energy dispersion under vertical shears *Geo. Res. Let.* **34**, L23807, doi:10.1029/2007GL031867.
- Ma, S.-H., A.-X. Qu, and Y. Wang, 2007: The Performance of the New Tropical Cyclone Track Prediction System of the China National Meteorological Center, *Meteor. Atmos. Phys.*, **97**, 29-39.
- Peng, J., T. Li, and M. Peng, 2008: Formation of tropical cyclone concentric eyewalls by wave-mean flow interactions. *Advances in Geosciences*, in press.
- Stowasser, M., Y. Wang, and K.P. Hamilton, 2007: Tropical cyclone changes in the western North Pacific in a global warming scenario. *J. Climate*, **20**, 2378-2396.
- Ventham, J. D., and B. Wang, 2007: Large Scale flow patterns and their influence on the intensification rates of Western North Pacific tropical storms. *Mon. Wea. Rev.*, **135**, 1110-1127.
- Wang, Y., 2007: A multiple nested, movable mesh, fully compressible, nonhydrostatic tropical cyclone model - TCM4: Model description and development of asymmetries without explicit asymmetric forcing. *Meteor. Atmos. Phys.*, **97**, 93-116.
- Yang, B., Y. Wang, and B. Wang, 2007: The effects of internally generated asymmetries on tropical cyclone potential intensity. *J. Atm. Sci.*, **64**, 1165-1188.
- Zhao, Y., B. Wang, and Y. Wang, 2007: Initialization and simulation of a landfalling typhoon using a variational bogus mapped data assimilation (BMDA), *Meteor. Atmos. Phys.*, **98**, 269-282.
- Zhou X. and B. Wang, 2007: A transition from an upper tropospheric mixed Rossby-gravity wave to tropical cyclone. *Geo. Res. Let.* **34**, L24801, doi: 10.1029/2007GL03183
- Zeng, Z., Y. Wang, and C.-C. Wu, 2007: Environmental dynamical control of tropical cyclone intensity-An observational study. *Mon. Wea. Rev.*, **135**, 38-59.

2008

- Wang B. and X. Zhou, 2008: Climate variation and prediction of rapid intensification in tropical cyclones in the western North Pacific. *Meteor. Atmos. Phys.*, **99**, 1-16.
- Wu, L., B. Wang, 2008: What changed the proportion of intense hurricanes in the last 30 years? *J. Climate*, **21**, 1434-1441.
- Wang, Y., 2008: Rapid filamentation zone in a numerically simulated tropical cyclone. *J. Atmos. Sci.*, **65**, 1158-1181.
- Wang, Y., 2008: Structure and formation of an annular hurricane simulated in a fully-compressible, nonhydrostatic model – TCM4, *J. Atmos. Sci.*, *J. Atmos. Sci.*, **65**, 1505-1527.
- Wu, C.-C., H.-J. Cheng, Y. Wang, and K.-H. Chou, 2008: A numerical investigation of the eyewall evolution of a landfalling typhoon. *Mon. Wea. Rev.* (in press)
- Wu, L., B. Wang, and S. A. Braun, 2008: Implications of tropical cyclone power dissipation index (PDI). *International J. Climatology*, **28**: 727–731. DOI: 10.1002/joc.1573.
- Zhao, H., D.-L. Tang, and Y. Wang, 2008: Comparison of phytoplankton blooms triggered by two typhoons with different intensities and translation speeds in the South China Sea. *J. Geophys. Res.-Ocean*, **365**, 57-65, doi:10.3354/meps07488.
- Zeng, Z., L.-S. Chen, and Y. Wang, 2008: An observational study of environmental dynamical control of tropical cyclones intensity in the North Atlantic. *Mon. Wea. Rev.*, **136**, 3307–3322.

Submitted manuscripts:

- Ge X., T. Li and M. Peng 2008: Simulation of Typhoon Prapiroon (2000) genesis associated with Rossby wave energy dispersion. Submitted to *Mon. Wea. Rev.*
- Kazuyoshi K., B. Wang and H. Fudeyasu 2008: *Genesis of tropical cyclone Nargis revealed by multiple satellite observations. Submitted to G.R.L*
- Fudeyasu, H., Y. Wang, M. Satoh, T. Nasuno, H. Miura, and W. Yanase, 2008: The global cloud-resolving model NICAM successfully simulated the lifecycles of two real tropical cyclones. *Geophys. Res. Lett.*, (revised).
- Wang, Y., 2008: How do outer spiral rainbands affect tropical cyclone structure and intensity? *J. Atmos. Sci.*, (in revision).
- Wang, Y.-Q., Y. Wang, and H. Fudeyasu, 2008: A numerical study of the effect of Typhoon Songda (2004) on remote heavy rainfall in Japan, *Mon. Rev. Rev.*, (revised).
- Yu, J.-H., Y. Wang, and K. Hamilton, 2008: Response of tropical cyclone potential intensity to the global warming scenario in the IPCC AR4 CGCMs. *J. Climate*, (submitted).
- Zhou X. and B. Wang 2008: From Concentric Eyewall to Annular Hurricane: A Numerical Study with the Cloud-Resolved WRF Model. Submitted to *GRL*.